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COMPUTER ANALYSIS OF STRESS-STRAIN DATA: PROGRAM DESCRIPTION AND USER INSTRUCTIONS

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ABSTRACT

A program description is given for a computer program which fits analytical expressions to experimental stress-strain, tension, or compression data. For stress values up to approximately the 0.2% offset yield strength, the three parameters for the Ramberg-Osgood description are determined; for values in excess of the yield strength the two constants for a simple strain-hardening power law are found. Other quantities which are also derived from the data include several yield strengths, plastic strain components, tangent moduli, and values of Poisson's ratio. Simple statistical calculations are also made to indicate to the user the goodness-of-fit of the analytical expressions to the experimental data. The three Ramberg-Osgood parameters, together with the two strain-hardening parameters and the end point of the data need only be stored for a simple data bank of stress-strain properties, since with these parameters the engineering, stress-strain curve can be reproduced. A sample of the output data is given.

CONTENTS

I. INTRODUCTION

This report describes a computer curve-fitting program for experimental, monotonically increasing stress-strain data. In its present state of development the program is useful for stress-strain curves which have a knee and strain hardening. For data from zero to approximately the 0.2% offset yield strength, a modified form of the Ramberg-Osgood[1] equation is used. Data beyond the yield in the strain-hardening region are approximated by a simple power law. The computer program also makes calculations of other stress-strain quantities as will be subsequently described.

Ramberg-Osgood Equation

Only three constants are required to characterize the data in the Ramberg-Osgood equation, which has the form

$$e = S/E + K(S/E)^m \tag{1}$$

where e = engineering strain
S = engineering stress

and the three constants are

E = Young's modulus
K = constant
m = exponent.

The constant K is a function of Young's modulus and a quantity designated in Reference 1 as the secant yield strength S_1. This is defined as the stress value of the intersection with the stress-strain curve of a line through the origin of slope 0.7E. This particular value of secant modulus results in a value of S_1 which is close to the 0.2% offset yield strength. A variation of Equation 1 is used in the computer program of the form

$$e = S/E + (3/7)(S_1/E)(S/S_1)^m. \tag{2}$$

Two of the original Ramberg-Osgood parameters have been retained in the current work. For the third parameter, S_1 has been used rather than K. As shown in Reference 1, S_1 and K are related by:

$$K = (3/7)(E/S_1)^{m-1}. \tag{3}$$

The choice to use S_1 rather than K as the third parameter was influenced by the fact that S_1 can be directly associated with a physical quantity, a yield strength, while K cannot. It also serves as the upper limit of stress for which the Ramberg-Osgood equation is applicable.

Values of the exponent m are related to the shape of the knee of the stress-strain curve. These ordinarily range from 10 to 100: the larger is the value of m, the sharper is the knee of the curve.

1. RAMBERG, W., and OSGOOD, W. R. *Description of Stress-Strain Curves by Three Parameters.* NACA TN 902, July 1943.

Strain-Hardening Equation

Analyses of stress-strain data from a number of different materials have shown that Equation 2 will closely approximate experimental values up to S_1, but beyond this point there is generally a poorer fit. However, a simple power law of the form

$$S = Ae^p \tag{4}$$

shows excellent agreement with test data in the strain-hardening region beyond a stress value of S_1. The two constants of Equation 4 are designated as follows:

A = strain-hardening coefficient
p = strain-hardening exponent.

One other constant is required to characterize the data, namely, the end stress or strain value of the monotonically increasing region of the stress-strain curve (which may or may not be the end-point of the test).

Plastic Strain Components

It is assumed that the proportional limit stress is the upper limit of elastic behavior as well as the limit of proportionality between stress and strain. This assumption is consistent with the ASTM definition[2] of the proportional limit as the "highest stress for which the offset is not measurable with the instrument used." On the basis of this definition, strains beyond the proportional limit can be considered to consist of two components: an elastic component e_e and a plastic component e_p.

The elastic component is defined as

$$e_e = S/E. \tag{5}$$

The plastic component is

$$e_p = e - S/E. \tag{6}$$

It is possible to relate the applied stress to the plastic component of strain by fitting equations of the form of Equation 4 to the appropriate data. The values of the coefficients and exponents of such equations can serve as quantitative measures of plastic behavior. Effects of various test environments and varying thermomechanical treatments on the plastic response of materials will be manifested by varying values of the parameters.

In a few materials one equation of the form of Equation 4 serves to describe the plastic properties from the proportional limit to the maximum value of engineering stress. In most materials a better fit of the data results when two equations are used: one equation from the proportional limit to some intermediate

2. *Standard Test Methods of Metallic Materials.* Designation E8-69, 1974, Annual Book of ASTM Standards, Part 7, Philadelphia, American Society for Testing and Materials, 1974, p. 578-598.

point in the yield region, and a second equation to apply from the intermediate point to the maximum values. In the computer program a two-equation description is used. The equations have the form

$$S = A_1 e_p{}^q \tag{7}$$

which applies from the proportional limit to the intermediate point and

$$S = A_2 e_p{}^r \tag{8}$$

which applies from the intermediate point to the maximum value.

The basic calculations to determine the constants for Equations 7 and 8 are first made with the stress S_1 as the intermediate value. In an optional-to-the-user calculation other intermediate stresses are used.

Computed Stress-Strain Properties

The two terms on the right-hand side of Equation 2 are an elastic strain component and a plastic strain component. Quantities such as the proportional limit and various yield strengths can be calculated from the plastic strain term. In the computer program, a value of the proportional limit is computed on the assumption that at this value of stress the plastic component will have a value of one microinch/inch. This strain is below the threshold of most extensometers and is consistent with the ASTM definition. A similar calculation is made to determine the 0.2% offset yield stress in which the plastic component is 0.2% strain. Calculations of the corresponding strain values are also made.

Statistical Evaluation

The average deviation of the analytical from the observed stress values, defined as the square root of the average of the squared deviations, is computed separately for each of three regions of the stress-strain curve: elastic, knee region (from the proportional limit to a stress of S_1), and strain hardening (for stress values in excess of S_1). The deviation values are a quantitative measure of how well the analytic expressions fit the observed experimental data. A similar statistical evaluation is made of the plastic strain component equations.

Abort Criteria

Included in the program are criteria to determine whether sufficient data have been supplied for a valid curve-fitting analysis to be made. If the criteria are not met, either the calculations are modified or the program is aborted.

Applications

Since it is possible to characterize a set of engineering stress-strain data with the five constants of Equations 2 and 4 and a value of S_{max} or e_{max}, it becomes unnecessary to keep a readily accessible file of stress-strain curves. Instead, the six constants need only be stored for ready access since these can be used to reproduce the experimental data. A file of these constants on punch cards, tape, or other permanent storage means can become a data bank of stress-strain properties. Accessing of the data can be made in any number of ways depending upon how the data are filed.

Comparisons between the properties of individual specimens can be made by comparing the values of the corresponding constants both for the engineering stress-strain data and the plastic strain components. Such comparisons could also reveal the effects of environmental conditions of test, heat treatment, etc., on the properties of materials.

The use of an analytic formulation for stress-strain data is of value in structural calculations involving elastic-plastic response. Historically, the Ramberg-Osgood formulation was developed for aircraft design using sheet materials where various moduli were required in the relations to predict elastic and plastic buckling.

II. METHOD OF ANALYSIS

Separate analyses are made to obtain the appropriate constants for the various analytic expressions.

1. Elastic modulus and intercepts of the elastic data on the stress and strain axes.

2. Ramberg-Osgood constants S_1 and m of Equation 2.

3. Strain-hardening constants A and p for the engineering stress-strain curve of Equation 4.

4. Strain-hardening constants A_1, q, A_2, and r for the stress-plastic strain curves of Equations 7 and 8.

A schematic flow chart is shown in Figure 1. Some specific details of the analyses which are not given on the flow chart are described in this section.

Elastic Analysis

A linear least-squares analysis is performed on all the data below an input proportional limit to obtain a value of Young's modulus. The intercept value, which is also calculated, represents the intersection of the elastic line and the stress axis as shown in Figure 2. It is assumed, however, that the data should pass through zero and that initial effects in the extensometer in the low loading region of the test are more likely to cause a nonzero intersection than effects in the loading system. On the basis of these assumptions, the strain intercept value, shown as e_o in Figure 2, is calculated and then algebraically subtracted from all the input strain values before further analyses are performed. This forces the analytic stress-strain curve to pass through zero. The new strain values are designated as adjusted strains.

After the Ramberg-Osgood analysis is completed a new proportional limit is specified based upon the Ramberg-Osgood equation. The elastic and Ramberg-Osgood analyses are then repeated. This second iteration obviates the need for the user to enter a precise value of the proportional limit as input to the program. The only requirement is that the input proportional limit be an elastic value.

Ramberg-Osgood Constants

In determining the values of S_1 and m, methods originally proposed in Reference 1 were adapted for the computer. As previously indicated, and shown in Figure 3, the value S_1 lies at the intersection of a secant modulus of slope equal to 0.7E with the stress-strain curve. After S_1 has been determined, Ramberg and Osgood suggested that a second secant modulus of slope equal to 0.85E be drawn to intersect the stress-strain curve. The point of intersection would have the values S_2 for stress and e_2 for strain. Once these values are determined they can be substituted into Equation 2 together with the values of E and S_1 and the equation can be solved for m resulting in

$$m = \log(3S_1(Ee_2 - S_2)/7)/\log(S_2/S_1). \tag{9}$$

The probability is quite small that in a set of experimental stress-strain data there will be individual values whose secant moduli are exactly 0.7E and 0.85E. It is more likely that the values S_1 and S_2 will lie between pairs of adjacent experimental points. These pairs of points are located by a search procedure which will also locate data whose secant moduli are exactly the required values.

Let the experimental data be designated as S_i and e_i where i varies from 1 to N, and where N is the total number of data points. Assume also that the data are entered into the computer in monotonically increasing order of stress value. In the search procedure for S_1, the quantity ΔS_i is defined as

$$\Delta S_i = S_i - 0.7Ee_i. \tag{10}$$

This quantity will be positive for all values of S_i which are less than S_1 and it will be negative for all values of S_i which are in excess of S_1 ($\Delta S_i = 0$ for a data value whose secant modulus is exactly 0.7E). Assume now that the value S_1 lies between the data points S_j and S_{j+1} as shown in Figure 4. The quantity S_j, computed according to Equation 10, will be positive while the quantity S_{j+1} will be negative. In the computer program, the quantities S_j and S_{j+1} are found for successive pairs of data points or in a systematic search procedure, and after each computation the ΔS values are compared for sign until a change in sign is discovered. This change in sign locates the points S_j and S_{j+1}.

The constants for the equation of a straight line connecting S_j and S_{j+1} are now found. The parameter S_1, which is taken as the intersection of this straight line with secant modulus line of slope 0.7E, can now be calculated. The linear approximation, which is assumed for the stress-strain curve between S_j and S_{j+1}, is reasonable if the difference between the two stress values is not large. This has generally been the case with a number of sets of data which have been analyzed.

A similar search procedure is used for finding S_2. Here ΔS_i is defined as

$$\Delta S_i = S_i - 0.85Ee_i. \tag{11}$$

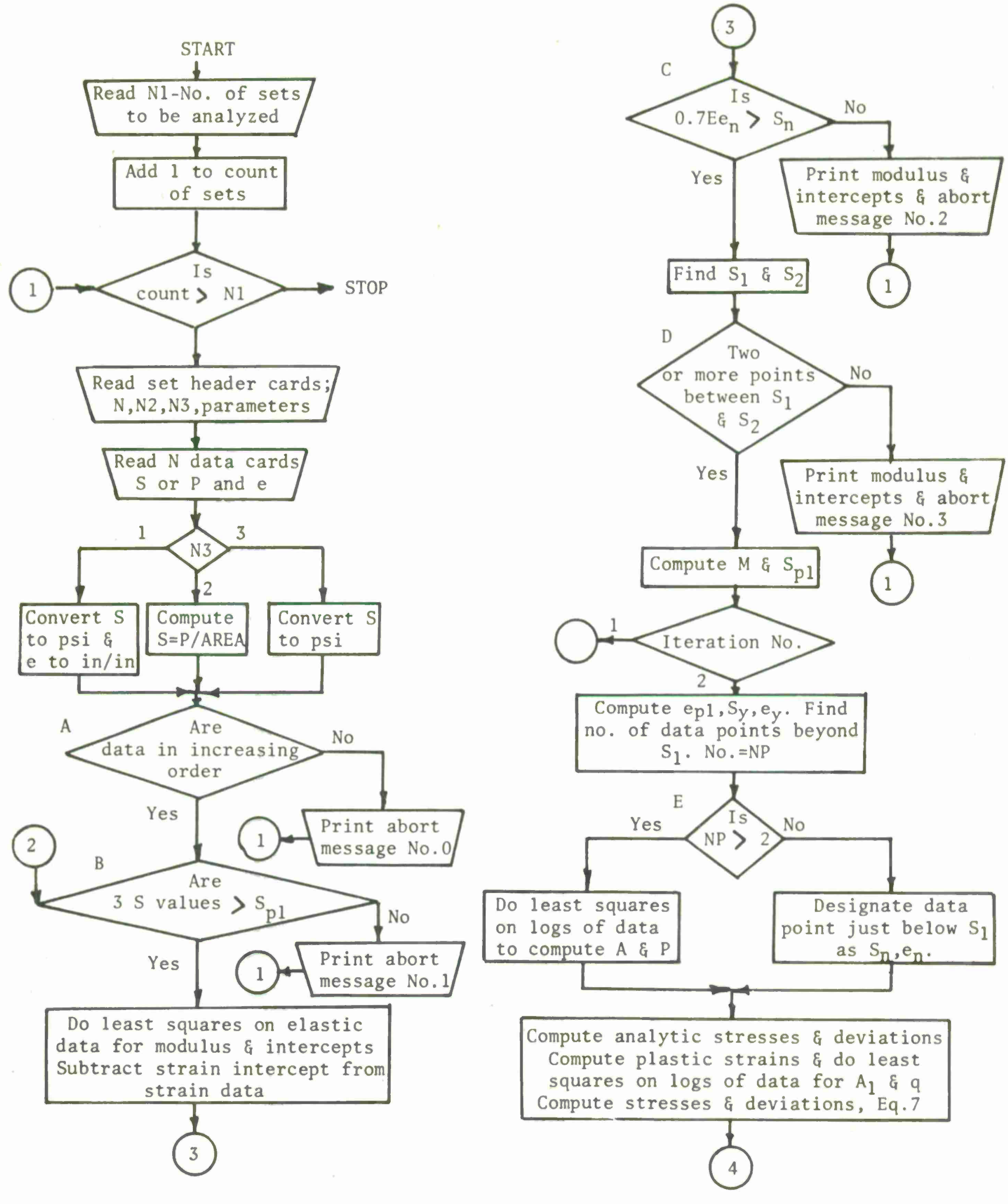
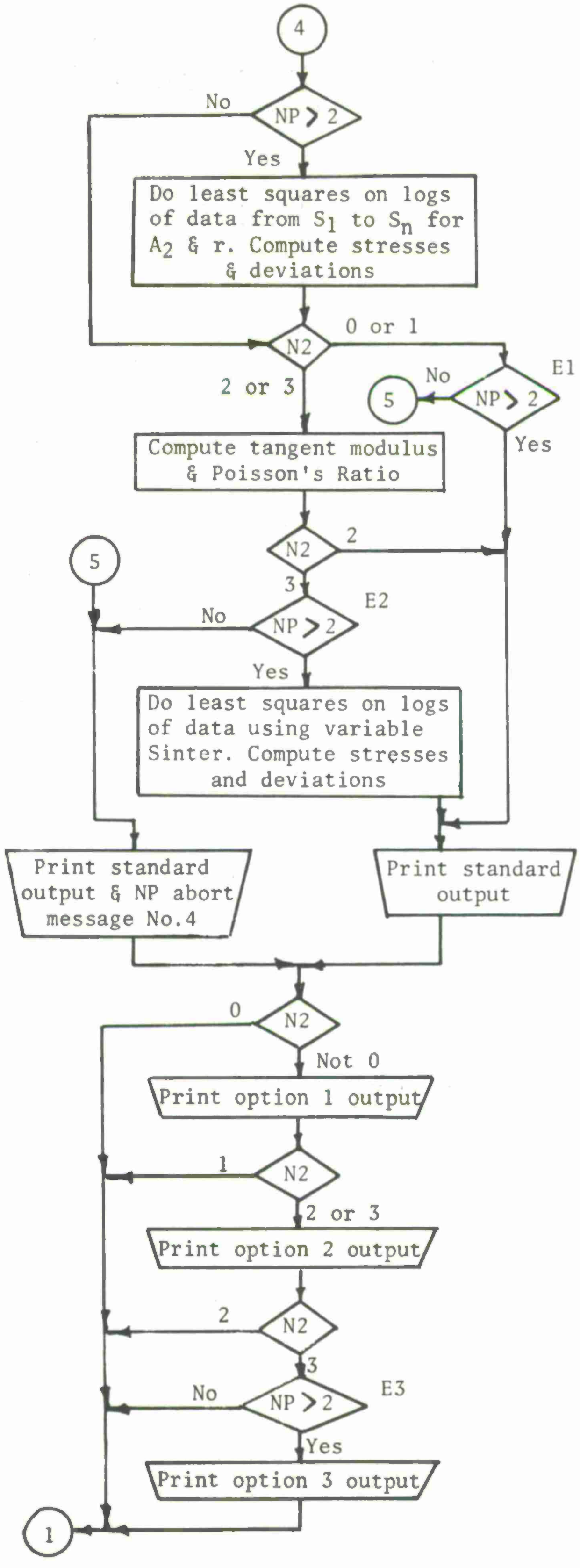


Figure 1. Flow chart of program (schematic). Letter identifiers A through E refer to Section IV of the text. Coded indicators N, N1, N2, N3, and NP are defined at the end of the chart.



GLOSSARY OF INDICATORS

N Number of data points in a set. One data point consists of a stress & a strain value

N1 Number of data sets to be analyzed

N2 Option number for output (When N2=0 only standard output is printed)

N3 Units used for input data
N3=1: ksi & micro-in/in
N3=2: lb & in./in.
N3=3: ksi & in./in.

NP Number of input data points for $S > S_1$

(Figure 1 Continued)

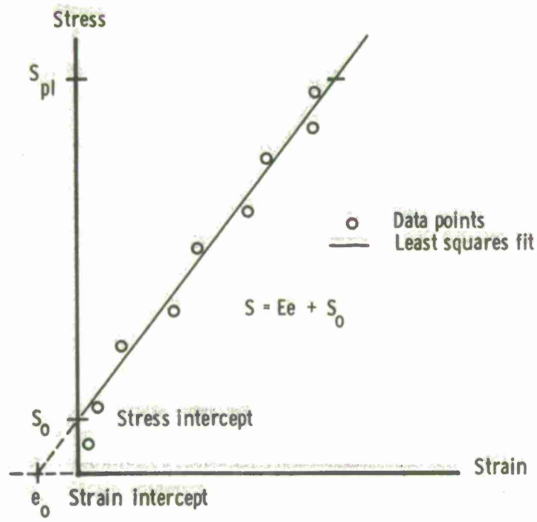


Figure 2. Stress and strain intercepts of least-squares straight-line fit of elastic data (schematic).

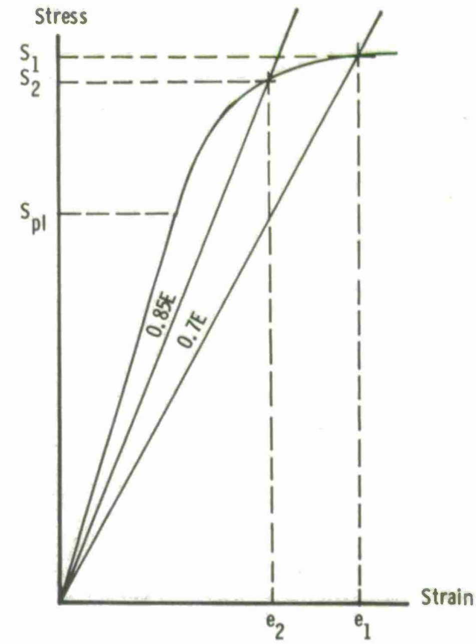


Figure 3. Stress-strain curve showing secant moduli used in Ramberg-Osgood analysis (schematic).

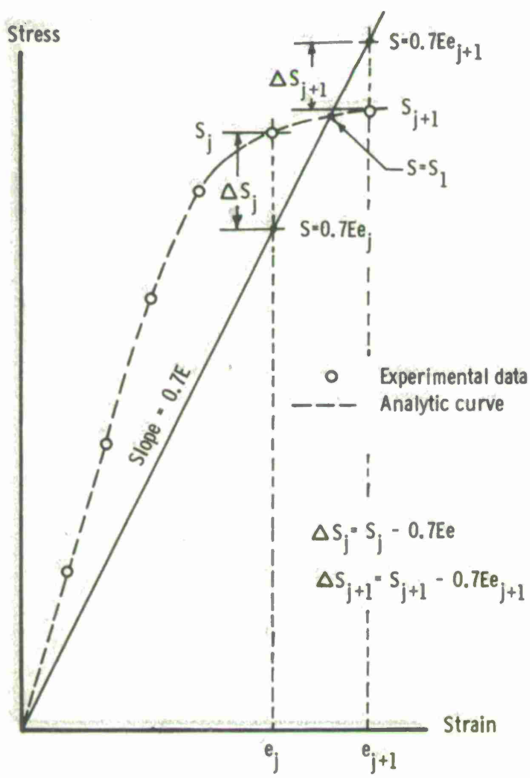


Figure 4. Location of parameter S_1 between S_j and S_{j+1} (schematic). The quantity S_j is positive and S_{j+1} is negative.

The strain value e_2 is calculated from

$$e_2 = S_2/0.85E. \tag{12}$$

The parameter m is then calculated from Equation 9.

It is now possible to calculate a more precise value of proportional limit. The second term on the right-hand side of Equation 2 is the plastic component of strain given as

$$e_p = (3/7)(S_1/E)(S/S_1)^m. \tag{13}$$

If e_p is set equal to 10^{-6} inch/inch, a value of S can be found from Equation 13 which can be considered as the proportional limit. This is done in the program and a second elastic analysis is made using the calculated S_{p1} as the criterion value. Then a second Ramberg-Osgood analysis is performed and it is the result of the second analyses which are printed out in the program.

Strain-Hardening Constants

Since the strain-hardening relation, Equation 4, is linear in logarithmic coordinates, a linear least-squares analysis is performed on the strain-hardening data to obtain the parameter p. In order to assure that Equation 4 will connect with Equation 2, it is assumed that the point (S_1, e_1) will lie on the curve of Equation 4. On the basis of this assumption, the value of A is determined from

$$A = S_1/e_1P. \tag{14}$$

Plastic Component Analysis

The plastic components of strain beyond the proportional limit are found by subtracting the elastic component from the total strain, as in Equation 6. The constants for Equations 7 and 8, describing the stress versus plastic component behavior, can now be determined.

Referring to Figure 5, it is assumed that the intermediate stress S_{inter} is equal to S_1. Linear least-squares analyses of the logarithms of the data from S_{p1} to S_1 are now performed to obtain the constants A_1 and q of Equation 7 and for the data values in excess of S_1 for A_2 and r of Equation 8. The four plastic component parameters are printed as part of the standard output of the program.

It is possible that the parameters for Equations 7 and 8 determined for a lower intermediate stress value than S_1 will give a better fit to the data. As an optional feature of the program, which the user can specify in the input, a series of calculations are made in which the intermediate stress is varied. For the first calculation, S_{inter} is chosen such that the first three data points beyond S_{p1} are used in the analysis for Equation 7 and the remainder of the higher value data points for Equation 8. On each subsequent calculation, S_{inter} is increased so that one additional data point is included for the Equation 7 analysis and one fewer for that of Equation 8. The calculations are continued until the value of S_{inter} becomes S_1.

Statistical Evaluation of Fit

When a curve-fitting procedure has been used on experimental data, it is appropriate that a quantitative measure be made of the goodness-of-fit of the data to the analytic approximations. This is done in the program by the calculation of the average deviations of the computed from the observed stress values.

The individual deviation is defined as

$$D_i = S_i - S_{ci} \qquad (15)$$

where S_i = an observed stress value
S_{ci} = computed stress for the adjusted strain e_i.

The average deviation D_{ave} for a range of n data values is defined as

$$D_{ave} = (\Sigma D_i{}^2/m)^{\frac{1}{2}}. \qquad (16)$$

In the program, analytical stress values are calculated, and the individual and average deviations are found for the data in the following categories:

A. Engineering Stress-Strain Curve

1) elastic data for values below S_{pl}
2) stress values from S_{pl} to S_1
3) stress values from S_1 to S_{max}.

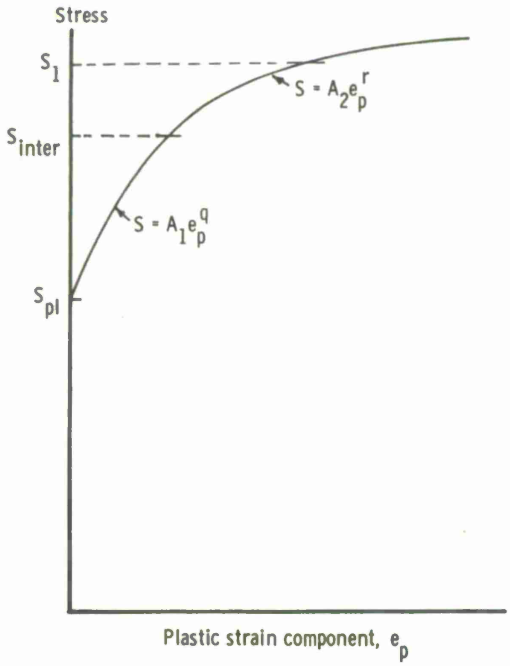


Figure 5. Two-equation analytical description of plastic strain components with a variable intermediate boundary stress (schematic).

B. Stress-Plastic Strain Component

1) from S_{pl} to S_1 using Equation 7
2) from S_1 to S_{max} Equation 8
3) in the optional calculation with variable S_{inter}

   a) from S_{pl} to S_{inter} using Equation 7
   b) from S_{inter} to S_{max} using Equation 8.

The statistical calculations for deviations of Equations 7 and 8 when S_{inter} is variable are made in a subroutine of the program.

Analytical Stress Calculations

Direct calculations of stress can be made for given values of engineering strain for the elastic data and by the use of Equation 4 for the plastic data. Stress values for the plastic strain components can be calculated from Equations 7 and 8. However, Equation 2, the Ramberg-Osgood equation, cannot be solved explicitly for stress when a given value of strain is specified. An iterative numerical scheme was therefore employed in the program to calculate the analytic stresses.

In developing the numerical procedure, Equation 2 was transformed to an equation in the variable $Z = S_c/S_1$

$$Z + (3/7)(Z)^m - Ee/S_1 = 8 \tag{17}$$

where S_c is the analytical value to be calculated.

The variable Z is nondimensional and has an upper limit value of $Z_{max} = 1$. The lower limit value can also be specified as $Z_o = S_{pl}/S_1$. A trial value of Z in Equation 17, designated as Z_t for a given value of strain e_i, will not generally cause the right-hand side to vanish. Rather there will be a residual:

$$Z_t + (3/7)Z_t{}^m + Ee_i/S_1 = \text{Residual}. \tag{18}$$

It is then assumed that a solution is obtained when the trial value of Z leads to a residual which is less than 10^{-5}. In the program a formalized scheme for incrementing Z iteratively with progressively smaller increments is used to obtain a solution. With this scheme and the criterion value of the residual, a solution value of Z accurate to the fifth significant figure can be obtained after approximately twenty iterations. A subroutine of the program is used for these computations.

Tangent Modulus

Differentiation of Equation 2 with respect to strain and rearranging terms results in

$$dS/de = E_t = E/(1 + (3m/7)(S/S_1)^{m-1}). \tag{19}$$

Since for stress values up to the proportional limit, $E_t = E$, Equation 19 is applied over the range $S_{pl}<S<S_1$. It should be noted that the analytic value of stress is used in calculating E_t from Equation 19. Differentiation of Equation 4 results in

$$E_t = Ape^{p-1} \tag{20}$$

which applies for $S>S_1$.

An output listing is given of values of the tangent modulus for every adjusted strain value; also included are values of the calculated stress.

Poisson's Ratio

In computing the value of Poisson's ratio beyond the proportional limit, the following assumptions are made.

1. The transverse strain consists of two components: one contributed by the longitudinal elastic strain component, and a second by the longitudinal plastic component.

2. The total transverse strain can be found from a law-of-mixtures addition of the two components.

3. Incompressibility applies to the plastic components so that Poisson's ratio for the plastic components is 0.5.

4. The material is isotropic.

These assumptions lead to the following definition of the transverse strain:

$$e_t = \mu e = \mu_e e_e + 0.5e_p \tag{21}$$

where e_t = transverse strain
μ = computed Poisson's ratio
e = total longitudinal strain
μ_e = elastic Poisson's ratio
e_e = elastic strain component, Equation 5
e_p = plastic strain component, Equation 6.

Substituting Equations 5 and 6 into Equation 21 and solving for μ result in:

$$\mu = (\mu_e - 0.5)S/Ee + 0.5. \tag{22}$$

The elastic value of Poisson's ratio is part of the input data to the program. In the computation the adjusted value of strain and the corresponding analytic value of stress are used in Equation 22. The calculated Poisson's ratio values appear in the same listing as the tangent modulus.

III. SUMMARY OF INPUT AND OUTPUT DATA

Specific details of the input data and their required format are given in Section V of this report. Samples of the output printout are given in Appendix I.

Input

Three types of input information are required:

1. Control information for the program including coded indicators for: the number of data sets; the number of data points in a set; and their units of measurement; and the optional output desired.

2. Descriptive information on the specimen and the test.

3. Numerical test data and an approximate value of the proportional limit.

Load, rather than stress, may be input to the program; in this case the specimen area is required in the input. If the Poisson's ratio calculation is chosen as an option, the elastic value of the ratio is required as input.

Output

There is a standard printout which always appears when the program is run. In addition there are three tabular outputs which are components of the optional output as follows:

Listing 1. Comparison of Computed and Observed Stress
Listing 2. Tangent Modulus and Poisson's Ratio
Listing 3. Plastic Component Parameters with a Variable Intermediate Stress

The user may select to have none of the three listings printed or one of the following three options:

Option 1. Listing 1 only
Option 2. Listings 1 and 2
Option 3. All three listings

Standard Printout

The following information is given:

1. Specimen and test descriptive information.

2. Young's modulus and the intercepts of the elastic data on the stress and strain axes.

3. Ramberg-Osgood parameters S_1 and m, proportional limit stress and strain, and 0.2% offset yield stress and strain.

4. Strain-hardening parameters A and p for the engineering stress-strain curve.

5. Strain-hardening parameters A_1, A_2, q, and r for the stress-plastic strain component equations with $S_{inter} = S_1$.

6. Statistical average deviations of the calculated stresses for each of the analytic expressions.

Tabular Listing 1: Comparison of Computed and Observed Stress

Individual values are given of each of the following quantities.

1. Input stress, input strain, adjusted strain, and computed stress from Equation 2 or Equation 4

2. Deviation of each computed stress value, Equation 15

3. Plastic strain component values and computed stress from Equation 7 or Equation 8 with intermediate stress of S_1

4. Deviation of each computed stress value

Tabular Listing 2: Tangent Modulus and Poisson's Ratio

This listing includes individual values of:

1. Computed stress and adjusted strain

2. Tangent modulus and ratio of tangent modulus to elastic modulus

3. Poisson's ratio

Tabular Listing 3: Plastic Component Parameters with Variable Intermediate Stress

Included are values of the coefficients and exponents for the two-equation description of plastic strain components for a range of variable intermediate stresses as follows:

1. A_1 and q for Equation 7

2. Average deviation, Equation 16, for stresses predicted by Equation 7

3. Intermediate stress and associated plastic component of strain

4. A_2 and r for Equation 8

5. Average deviation, Equation 16, for stresses predicted by Equation 8

IV. PROGRAM ABORT CRITERIA

Calculations in the program will be completely or partially aborted when the input data do not meet certain criteria. In each case when such a premature termination occurs, a specific diagnostic statement will appear in the data printout. The criteria and the resulting modification of the computing procedure, when the criteria are not met, are discussed below as they are applied in the program. The tests of the data are indicated by letter identifiers on the flow chart (see Figure 1), which correlate with the letter identifier of the paragraph titles.

A. Order of Input Stress Data - The input test data must be arranged in increasing order of stress magnitude. If this criterion is not met, the calculations are terminated.

B. Elastic Data - At least three data values below the proportional limit are required before the least-squares analysis for modulus and intercepts will be performed. If this criterion is not met on the first or second iteration, the calculations are terminated.

C. Input Data to the Yield Stress - The stress value of the last input data point must equal or exceed the secant yield strength S_1. If this criterion is not met, the Ramberg-Osgood analysis and subsequent analyses are terminated and only the elastic data are printed out.

D. Knee-Region Data - At least two data points are required between S_1 and S_2 as shown in Figure 6. When fewer points are present the analyses are terminated as in C and only the elastic data are printed out.

E. Strain-Hardening Data - There must be at least three data points whose stress values are equal to or greater than S_1. If this criterion is not met, no strain-hardening analysis of the engineering stress-strain data is performed. The calculations which are performed and the output which is printed then depend upon what optional data have been requested from the program. The data which appear as output when the various printout options are requested are as follows:

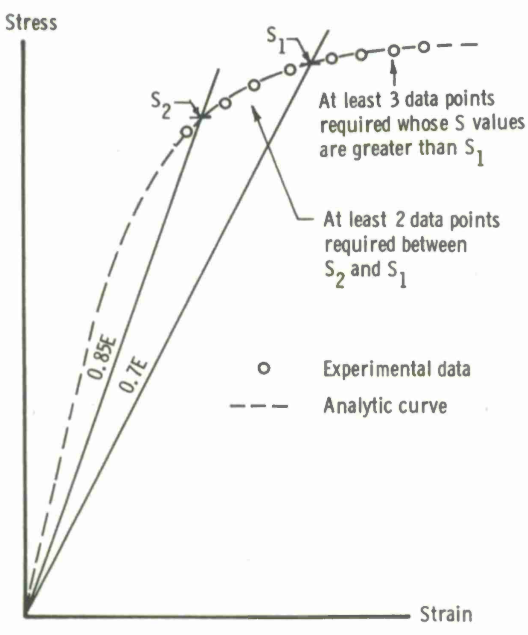


Figure 6. Stress-strain curve with data points in the vicinity of S_1 and S_2 (schematic).

1. No optional tabular data. Standard printout with the following omitted: a) strain-hardening data for Equation 2 and b) plastic component parameters for Equation 8.

2. Option 1. Standard printout as above and tabular values for all input data less than S_1 (E_1 on Figure 1).

3. Option 2. Same printout as in Option 1 plus tabular values of tangent modulus and Poisson's ratio for all input data less than S_1 (E_2 on Figure 1).

4. Option 3. Same as Option 2, since there are insufficient data beyond S_1 to evaluate the parameters for Equation 8 (E_3 on Figure 1).

V. USER INPUT DATA

The program requires that the data be entered into the computer on punch cards. Specific details of the input formats, columnar locations, etc., are given in a supplement* to this report. A summary of the information required on the data cards is given below and listed in Figure 7.

A typical data deck contains a deck header card followed by sets of stress-strain data cards, each set of which consists of a set header card followed by individual data cards, each containing one value of stress (or load) and one value of strain.

First Card: The deck header card requires the number of data sets to be analyzed (1 to 99 sets) entered in the first three columns and the date the program is run entered in columns 4 through 15.

Data Cards: Each set of data cards consists of a specimen header card followed by the individual data cards. The specimen header card requires the following information:

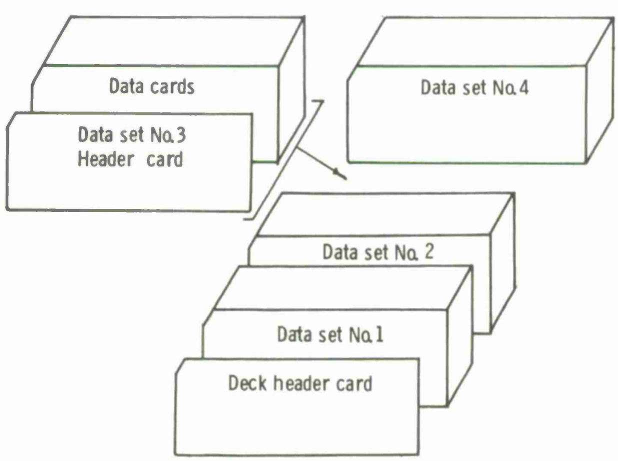


Figure 7. Data deck (schematic).
Maximum number of data sets is 99.
Maximum number of data cards per set is 99.

*PAPIRNO, R. Supplement to AMMRC TR 76-12. *Program Listing, Glossary and Specific User Instructions,* available from Mechanics Research Laboratory on request.

Specimen identifier:	6 columns
Material identifier:	12 columns
Test temperature:	6 columns
Test strain rate:	6 columns
Number of data cards:	3 columns
Input format coded indicator:	3 columns
Proportional limit stress:	7 columns
Elastic Poisson's ratio:	5 columns
Specimen area:	7 columns (an entry is only required if the specimen load is used on the data cards)
Date of test:	12 columns
Output option coded indicator:	3 columns

The specimen data may be entered for any one set in one of three forms. In each case the stress or load value is entered in the first seven columns and the strain in the next seven columns. The three permissible combinations are as follows:

Stress in kilopounds per square inch, strain in microinches per inch.
Load in pounds, strain in inches per inch.
Stress in kilopounds per square inch, strain in inches per inch.

Specific information given in the supplement is sufficient to allow use of the program by those who have only a rudimentary knowledge of computer programming.

APPENDIX I. TYPICAL OUTPUT WITH OPTION 3

Sample of the printout for a specimen of ESR 4340 steel tested in compression at room temperature. The standard output and the three tables of Option 3 are shown.

```
              ANALYTIC APPROXIMATION OF STRESS-STRAIN PROPERTIES
               RAMBERG-OSGOOD AND STRAIN HARDENING PARAMETERS
                 OBTAINED FROM ANALYSES OF EXPERIMENTAL DATA
                        PROGRAM NUMBER ARPY5 MAY 75

                THE CALCULATIONS WERE PERFORMED ON  MAY 27,1975

      RAMBERG-OSGOOD EQUATION       EPS=SIG/E+(3/7)(S1/E)(SIG/S1)**M

      STRAIN HARDENING LAW          SIG=A(EPS)**P

SPEC. NO. ESR011   4340 STEEL    TEMP=  20   DEG. C    STRAIN RATE= 1.0-05 PER SEC    TEST DATE  DEC. 1974

      ELASTIC PARAMETERS                                    ELASTIC MODULUS, E=  29.60 MILLION PSI
      INTERCEPT ON STRESS AXIS=     110. PSI        INTERCEPT ON STRAIN AXIS=    -4. MICRO-IN/IN

       PARAMETERS DETERMINED AFTER ALGEBRAIC SUBTRACTION OF STRAIN OFFSET FROM RAW STRAIN DATA

      RAMBERG-OSGOOD PARAMETERS                        S1=  185.41 KSI           M=  57.08
      PROPORTIONAL LIMIT  (1 MICRO-IN/IN OFFSET)      SPL=  161.46 KSI         EPL= .005454 IN/IN
      0.2 PERCENT YIELD                                SY=  184.45 KSI          EY= .008231 IN/IN

      STRAIN-HARDENING PARAMETERS          COEFFICIENT  A= .2341+06              EXPONENT  P= .049433

         AVERAGE STATISTICAL DEVIATIONS OF COMPUTED STRESS VALUES FROM INPUT STRESS DATA
 FROM ZERO TO SPL    212. PSI     *****     FROM SPL TO S1    276. PSI     *****     FROM S1 TO SMAX   639. PSI

                        *    *    *    *    *    *    *    *    *

             STRAIN-HARDENING PARAMETERS FOR PLASTIC COMPONENTS OF STRAIN
                                  FOR EQUATIONS OF THE FORM
      SIG=A1(EPS-PLASTIC)**Q    FROM SPL TO S1  ****  SIG=A2(EPS-PLASTIC)**R    FROM S1 TO SMAX

         A1= .2066+06      Q= .01810                        A2= .2147+06      R= .02475

            AVERAGE STATISTICAL DEVIATION OF COMPUTED STRESS FROM OBSERVED VALUES
             FROM SPL TO S1   371. PSI     *****     FROM S1 TO SMAX     38. PSI
```

COMPARISON OF COMPUTED STRESS VALUES WITH EXPERIMENTALLY OBSERVED VALUES
FOR SPECIMEN NO. ESR011 DATE OF TEST DEC. 1974

STRESS-ENGINEERING STRAIN					STRESS-PLASTIC STRAIN COMPONENT		
OBSERVED STRESS KSI	OBSERVED STRAIN PCT	ADJUSTED STRAIN PCT	COMPUTED STRESS KSI	STRESS DEVIATION KSI	PLASTIC STRAIN PCT	COMPUTED STRESS KSI	STRESS DEVIATION KSI
.00	.0001	.0005	.14	-.140	.0000	.00	.000
10.30	.0342	.0346	10.23	.067	.0000	.00	.000
20.60	.0699	.0703	20.80	-.201	.0000	.00	.000
30.90	.1035	.1039	30.75	.153	.0000	.00	.000
41.20	.1397	.1401	41.46	-.262	.0000	.00	.000
51.50	.1727	.1731	51.23	.270	.0000	.00	.000
61.80	.2072	.2076	61.44	.358	.0000	.00	.000
72.10	.2433	.2437	72.13	-.028	.0000	.00	.000
82.40	.2772	.2776	82.16	.237	.0000	.00	.000
92.70	.3128	.3132	92.70	-.001	.0000	.00	.000
103.00	.3486	.3490	103.30	-.298	.0000	.00	.000
113.20	.3835	.3839	113.63	-.428	.0000	.00	.000
123.60	.4168	.4172	123.49	.115	.0000	.00	.000
133.80	.4512	.4516	133.67	.132	.0000	.00	.000
144.10	.4865	.4869	144.12	-.017	.0000	.00	.000
154.40	.5211	.5215	154.36	.041	.0000	.00	.000
164.70	.5562	.5566	164.66	.044	.0000	.00	.000
175.00	.6021	.6025	175.20	-.199	.0113	175.27	-.266
181.20	.6701	.6705	180.62	.582	.0583	180.56	.640
183.30	.7590	.7594	183.31	-.006	.1401	183.45	-.148
185.30	.8863	.8867	185.31	-.010	.2607	185.52	-.221
187.40	1.0471	1.0475	186.86	.544	.4144	187.42	-.024
189.50	1.2790	1.2794	188.71	.788	.6392	189.44	.055
190.30	1.4084	1.4088	189.61	.687	.7659	190.29	.005
190.70	1.4890	1.4894	190.14	.565	.8451	190.76	-.059
191.10	1.5520	1.5524	190.53	.575	.9068	191.09	.009

TANGENT MODULUS VALUES AND POISSON'S RATIO
SPECIMEN NUMBER ESR011 DATE OF TEST DEC. 1974

COMPUTED STRESS KSI	ADJUSTED STRAIN PCT	TANGENT MODULUS PSI	TANGENT MODULUS RATIO	COMPUTED POISSON'S RATIO
.14	.000	.2960+08	1.0000	.2800
10.23	.035	.2960+08	1.0000	.2800
20.80	.070	.2960+08	1.0000	.2800
30.75	.104	.2960+08	1.0000	.2800
41.46	.140	.2960+08	1.0000	.2800
51.23	.173	.2960+08	1.0000	.2800
61.44	.208	.2960+08	1.0000	.2800
72.13	.244	.2960+08	1.0000	.2800
82.16	.278	.2960+08	1.0000	.2800
92.70	.313	.2960+08	1.0000	.2800
103.30	.349	.2960+08	1.0000	.2800
113.63	.384	.2960+08	1.0000	.2800
123.49	.417	.2960+08	1.0000	.2800
133.67	.452	.2960+08	1.0000	.2800
144.12	.487	.2960+08	1.0000	.2800
154.36	.521	.2960+08	1.0000	.2800
164.66	.557	.2870+08	.9695	.2801
175.20	.602	.1464+08	.4946	.2839
180.62	.670	.4458+07	.1506	.2998
183.31	.759	.2127+07	.0719	.3206
185.31	.887	.1195+07	.0404	.3447
186.86	1.047	.8818+06	.0298	.3674
188.71	1.279	.7292+06	.0246	.3904
189.61	1.409	.6653+06	.0225	.4000
190.14	1.489	.6311+06	.0213	.4051
190.53	1.552	.6067+06	.0205	.4088

STRAIN-HARDENING COEFFICIENTS AND EXPONENTS FROM A TWO EQUATION ANALYSIS OF THE STRESS-PLASTIC STRAIN COMPONENT DATA USING A VARIABLE INTERMEDIATE STRESS VALUE.

SPECIMEN NUMBER ESR011   DATE OF TEST DEC. 1974

EQUATION 1 PARAMETERS ARE FOR VALUES OF STRESS FROM 175.00 KSI TO AN INTERMEDIATE POINT IN THE R-O REGION

EQUATION 2 PARAMETERS ARE FOR VALUES OF STRESS FROM THE INTERMEDIATE POINT TO A MAXIMUM STRESS OF 191.10 KSI

EQUATION 1 PARAMETERS			INTERMEDIATE POINT			EQUATION 2 PARAMETERS		
COEFF. A1	EXPONENT Q	DEVIATION KSI	OBSERVED STRESS KSI	PLASTIC STRAIN PCT	SECANT MODULUS RATIO	COEFF. A2	EXPONENT R	DEVIATION KSI
.2077+06	.01874	.223	183.30	.4144	.815	.2146+06	.02468	.014
.2066+06	.01810	.186	185.30	.6392	.706	.2147+06	.02475	.017
.2071+06	.01840	.156	187.40	.0000	.604	.2135+06	.02362	.021
.2080+06	.01897	.165	189.50	.0000	.500	.2145+06	.02457	.019

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